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REPORT NO T95-4

HUMAN FLUID BALANCE AND DEHYDRATION DURING COLD WEATHER MILITARY OPERATIONS

U.S. ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

UNITED STATES ARMY
MEDICAL RESEARCH & MATERIEL COMMAND

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
December 1994

3. REPORT TYPE AND DATES COVERED
Technical Note

4. TITLE AND SUBTITLE
Human Fluid Balance and Dehydration During Cold Weather Military Operations

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Same as Block 7.

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Not unlike exposure to hot environments, exposure to the cold can disrupt body fluid balance. While the mechanisms responsible for cold-induced dehydration (i.e., cold diuresis, increased respiratory water loses, fluid losses associated with wearing bulky winter clothing, poor fluid availability/delivery, inadequate thirst sensation,etc.) are somewhat different than those for hot environments, the impact of the fluid imbalance is often quite similar. For example, cold-induced dehydration can negatively influence both physical and cognitive performance as well as disrupt normal thermoregulation. It is also thought that dehydration may increase the susceptibility to peripheral cold injuries. This paper reviews the literature regarding factors influencing body fluid balance in the cold as well as the impact of the fluid imbalance on soldier performance and mission accomplishment. Described are potential countermeasures for preventing or delaying body fluid imbalances in the cold, including recent advances in hyperhydration techniques.

14. SUBJECT TERMS
Cold Diuresis, Cold Injury, Cold Stress, Dehydration, Fluid Balance

15. NUMBER OF PAGES
34

16. PRICE CODE
STO 3TB

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

TECHNICAL NOTE
NO. T95-4

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by

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DTIC AVAILABILITY NOTICE

LIST OF FIGURES

ACKNOWLEDGEMENTS

The authors thank Dr. Richard Gonzalez, Mr. Bill Matthew, Mr. Clement Levell and Mr. Leander Stroschein of the Biophysics and Biomedical Modeling Division of the U.S. Army Research Institute of Environmental Medicine, for their technical assistance and to Ms. Patricia DeMusis for her professional preparation of this manuscript.

EXECUTIVE SUMMARY

Not unlike exposure to hot environments, exposure to the cold can disrupt body fluid balance. While the mechanisms responsible for cold-induced dehydration (i.e., cold diuresis, increased respiratory water losses, fluid losses associated with wearing bulky winter clothing, poor fluid availability/delivery, inadequate thirst, etc.) are somewhat different than those for hot environments, the impact of the fluid imbalance is often quite similar. For example, cold-induced dehydration can negatively influence both physical and cognitive performance as well as disrupt normal thermoregulation. It is also thought that dehydration may increase the susceptibility to peripheral cold injuries. This paper reviews the literature regarding factors influencing body fluid balance in the cold as well as the impact of the fluid imbalance on soldier performance and mission accomplishment. Described are potential countermeasures for preventing or delaying body fluid imbalances.

INTRODUCTION

Water is the body's most important nutrient, accounting for nearly 70% of body weight in a normal adult. During rest in temperate climates, total body water is maintained within a narrow range i.e., approximately 0.2% of total body weight (Greenleaf, 1992). This tight balance is achieved through fluid ingestion associated with eating and drinking, coupled with metabolic water released and physiological systems that regulate fluid loss e.g., renal, cardiovascular, and hormonal.

During physical work, mental stress, and/or exposure to climatic extremes, marked disruptions of body fluid balance can occur. This is as true in cold as in hot climates. Daily body water transfer will approximate 2-3 liters/day for sedentary soldiers in temperate conditions, but can often range from 6-10 liters/day for active soldiers in hot and cold climates. If these water losses are not fully replaced, dehydration will occur. For example, soldiers conducting cold weather operations are often dehydrated by 3-8% of body weight (Bly et al., 1950; Rogers et al., 1964). These dehydration levels are similar in magnitude to those reported for persons in hot climates. Importantly, marked body water loss, if not replaced, will have a significant impact on the health and performance of soldiers.

While the importance of hydration on work performance has been recognized for years, relative to our understanding in hot climates, considerably less is known with regard to effects of cold climates. Few studies have specifically assessed the effects of cold-induced dehydration on physical work, thermoregulation or susceptibility to cold injuries. In fact, the two major review articles that have addressed fluid balance in the cold did not specifically discuss military aspects, implications, or concerns (Bass and Henschel 1956; Fregly, 1991). The importance of maintaining body hydration during military operations in the cold has been long appreciated.

For example, forty-five years ago a U.S. Army physician described what he felt were the nutritional problems/concerns associated with conducting military operations in Arctic climates and concluded,

"The most important problem yet to be solved is that of man's water balance" (Orth, 1949).

One can still argue the statement is as true today.

PROBLEM/SITUATION

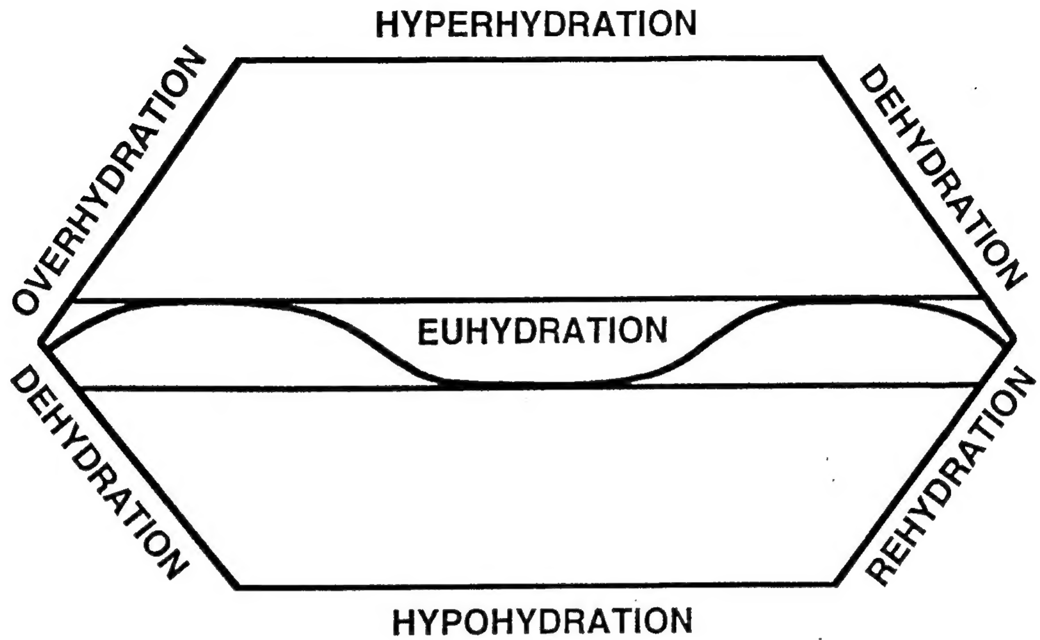
U.S. military forces must be prepared to deploy and successfully fight during cold weather conditions. Sixty percent of the earth's land mass has January temperature lows below 0°C (32°F), and over 25% of the earth's land mass experiences January temperature lows below -18°C (0°F) (Bates and Bilello, 1966). Furthermore, many national borders of military significance are located in mountainous regions that are not only at considerable altitude but, also extreme cold. As a result, it is not unrealistic to anticipate future military operations in cold cimates where body water deficits will be encountered by soldiers. Thus, it is critical we improve our understanding of the effects of cold on body fluid balance if we are to optimize the health and performance of soldiers deployed to these harsh environments.

This paper reviews: 1) factors that increase fluid loss and reduce fluid intake in cold climates; 2) the military impact or significance of dehydration in the cold; and 3) possible countermeasures to minimize dehydration in the cold.

BODY FLUID STATES

Figure 1 provides the terminology used in this chapter (Greenleaf, 1992). The terms, dehydration, rehydration and overhydration, refer to "processes" in which total body water is either increased or decreased; while the terms, euhydration, hypohydration, and hyperhydration indicate hydration status. Hyperhydration and hypohydration are used to refer to conditions in which hydration status, i.e., total body water, is greater or less than normal, respectively.

FIGURE 1



FACTORS CAUSING DEHYDRATION IN THE COLD

Several factors are associated with dehydration during cold exposure. While some of these cause increases in fluid losses, others are related to reductions in fluid intake. The most significant factors are considered in detail below.

INCREASED FLUID LOSSES IN THE COLD

Cold Induced Diuresis

Cold Induced Diuresis (CID) is one area regarding fluid balance in cold that has received considerable attention. Debate exists with regard to: 1) the significance or impact of CID; 2) the nature of the diuresis, i.e., free water diuresis or osmotic

diuresis; and 3) the physiological mechanism/s responsible for CID. The failure by investigators to control extraneous variables is partially responsible for the discrepancies in findings. Table 1 summarizes some of the key studies regarding CID in humans.

CID was first observed over 200 hundred years ago by Sutherland (Sutherland, 1764) who reported an increase in urine flow following cold water bathing. Sutherland, however, made no mention or speculation about the relative influence of water immersion versus that of cold exposure *per se*. It was not until 1909 that Gibson (Gibson, 1909) demonstrated an increase in urine flow was the direct result of cold exposure. In 1940 Bazett and associates (Bazett et al., 1940) published a field study which confirmed an increase in urine flow with cold exposure, and also demonstrated commensurate reductions in blood and plasma volumes.

Bader, et al., (Bader et al., 1952) demonstrated that confounding factors could influence the magnitude of CID and whether, or not, a diuresis even occurred during cold exposure. They reported that CID could be avoided if moderate exercise was simultaneously performed with cold exposure. Subsequent investigations demonstrated CID can be influenced by other factors such as: 1) the intensity and duration of cold exposure; 2) hydration status; 3) body posture during cold exposure; 4) performance of exercise; 5) diet; 6) gender; 7) age; 8) body composition; and 10) the time of day (Bader et al., 1952).

Lennquist and associates, et al., (Lennquist, 1974) attempted to determine mechanism/s responsible for CID, and these investigators provided evidence indicating CID was not the result of a fall in antidiuretic hormone (ADH) as was previously suggested (Bader et al., 1952; Eliot, et al., 1949) and commonly believed. With these findings, the notion that CID was simply a pressure diuresis reemerged; the logic being that the increased systemic arterial blood pressure, would increase renal blood pressure and thereby reduce tubular reabsorption of both water and solute i.e., electrolytes. Wallenberg and Granberg (Wallenberg and Granberg, 1976) demonstrated that the blood pressure increases during cold exposure were correlated to sodium excretion ($r \approx 0.60$) and hence, speculated that the mechanism for CID was, at least in part, the result of an increased in blood pressure. The hypothesis that CID

is a pressure diuresis is still favored by many investigators today and little direct evidence suggests otherwise.

Combined data in two publications from the U.S. Army Research Institute of Environmental Medicine (Muza et al., 1988; Young et al., 1987) suggests CID may not be a pressure diuresis. These two papers come from the same experiments in which subjects were immersed in cold water prior to and, following a 5-wk cold water acclimation program. Young and colleagues (Young et al., 1987) reported the CID response to cold water immersion was not affected by the cold acclimation regime, i.e., the magnitude of diuresis was the same during the initial pre-test as it was during the post-test. When reporting the cardiovascular data Muza et al., (Muza et al., 1988) showed that while mean arterial blood pressure was markedly increased during the initial cold water exposure, i.e., pre-test, it did not increase during the post-test. Together these data provide evidence that CID and blood pressure responses can be disassociated and hence, raises questions of the pressure diuresis hypothesis.

With regard to CID, the following conclusions can be made: 1) while there is disagreement regarding the mechanism/s, the central movement of fluid caused by peripheral vasoconstriction is likely involved; 2) if studies are to be meaningful, confounding factors must be controlled or specifically examined; 3) CID appears to be self-limiting, in that as dehydration occurs CID is reduced or eliminated.

TABLE 1 Significant Studies Regarding Cold Induced Diuresis

Reference	Environment/Situation	Findings
*Sutherland (1764)	Cold water bathing	↑Urine loses
*Gibson (1909)	Cold air (4-10°C)	↑Urine flow with ↓temperature
*Bazett *et al.* (1940)	2 weeks in cold climate	↑Urine flow, ↓B.V., ↓P.V.
Eliot *et al.* (1949)	Cold air (15°C)	↑Urine flow blocked by ADH
Bader *et al.* (1952)	Cold air (15°C)	Demonstrated confounding factors influence CID
Segar and Moore (1968)	Cold air (13°C)	↑Urine flow and ↓ADH
*Lennquist *et al.*(1974)	Cold air (15°C)	Examined mechanisms for CID concluded <u>not</u> ADH mechanism
Wallenberg *et al.* (1976)	Cold air (15°C)	Evidence CID <u>is</u> pressure natriuresis
Young *et al.* (1987) & Muza *et al.* (1988)	Cold water (18°C) with cold acclimated subjects	Evidence CID is <u>not</u> pressure diuresis
Various authors (1985-present)	Cold air and cold water	Conflicting findings regarding hormonally mediated or not, ADH, vs. ANF, vs. pressure

NOTE: * = "Field" studies or observations while others are laboratory experiments; ↑ = increase; ↓ = decrease; B.V. = blood volume; P.V. = plasma volume; ADH = antidiuretic hormone; CID = cold induced diuresis; ANF = atrial natriuretic factor.

Respiratory Water Losses

Although cold dry air is often credited as a contributor to fluid losses in cold environments, the magnitude of these losses are seldom reported. The amount of fluid loss via respiration is dependent on both the ventilatory volume as well as the water vapor in the ambient air (Brebbia et al., 1957). Respiratory water losses can be estimated from metabolic rate, and ambient air conditions, i.e., air temperature and relative humidity. Using predictive models (Brebbia et al., 1957; Mitchell et al., 1972), respiratory fluid losses were estimated for both rest and exercise conditions at three ambient temperatures and water vapor pressures (Table 2). Despite high relative humidities (100% used for demonstration) cold air contains significantly less water vapor than does warmer air of lower relative humidity. The difference in water vapor pressure between the saturated air in the lung (water vapor 44 mm Hg) and ambient air determines the amount of respiratory water lost with each breath. Hence, the lower the water vapor pressure in ambient air the greater the respiratory water losses.

Respiratory water loss increases with increasing metabolic rate because pulmonary ventilation is increased. To compare the effect of cold air and metabolic rate on respiratory water loss, we predicted respiratory water losses for a 24 h scenario in which a person rests for 8 h, performs moderate activity for 12 h, and performs strenuous work for 4 h (Table 2). Respiratory losses are approximately doubled at -20°C versus 25°C i.e., 0.68 vs 1.02 liters/24 hr (Table 2). Therefore, respiratory water losses can contribute to dehydration in the cold, although, metabolic rate has a far greater impact than ambient temperature on respiratory fluid losses and hence, fluid requirements.

TABLE 2 Effects of Ambient Temperature on Respiratory Water Loss

Temperature (°C)	r.h. (%)	Water Vapor (mmHg)	Metabolic Rate (W)	Respiratory Water (ml/h)
25	65	15	Rest (100)	~10
0	100	5	Rest (100)	~13
-20	100	1	Rest (100)	~15
25	65	15	Light-moderate (300)	~30
0	100	5	Light-moderate (300)	~40
-20	100	1	Light-moderate (300)	~45
25	65	15	Moderate-heavy (600)	~60
0	100	5	Moderate-heavy (600)	~80
-20	100	1	Moderate-heavy (600)	~90

If 8 Hour Rest, 12 Hour Light-Moderate Activity and 4 Hour Moderate-Heavy Activity

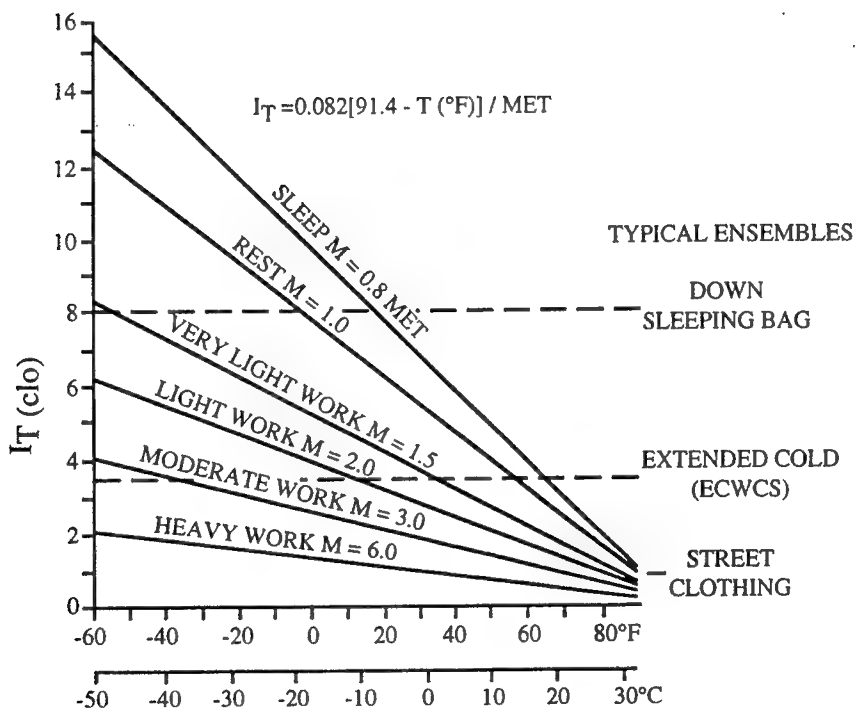
		Total Respiratory Loss
25	65	~680 ml/24h
0	100	~905 ml/24h
-20	100	~1020 ml/24h

NOTE: Effect of cold air itself could account for increased respiratory water losses as great as 340ml/24h i.e. 50% increase; r.h. = relative humidity; W = watts.

Cold Weather Clothing

A potentially important factor on water losses in the cold is the effect of bulky/heavy clothing. Significant metabolic heat can be generated during military activities and result in significant sweating even in cold climates. Figure 2 demonstrates the relationship of total insulation and metabolic rate on the thermal comfort of individuals exposed to different ambient temperatures (Gonzalez, 1988). The total insulation required to keep a resting person warm is considerably more than that required to keep a person warm who is performing moderate to heavy work/exercise (1 Clo unit is equivalent to the insulation of a business suit).

FIGURE 2



If clothing is not carefully matched to metabolic rate, significant heat storage and sweating can occur. Table 3 is provided as an example. Note that a person dressed in the U.S. Army Extended Cold Weather Clothing System (insulation ~ 4.0 Clo), produces little sweat while resting in the cold. However, if this person performed moderate or heavy exercise in that uniform, it is estimated that nearly 2.0 liters/hr of sweat would be lost. Since this clothing system allows for little evaporation, the uniform might become soaked. A wet uniform has serious implications for heat loss and subsequent cold injury susceptibility. If the cold weather clothing system is altered to reduce total insulation to a Clo of 1.9, sweating would be reduced five fold i.e., to about only 0.4 liter/hr (Table 3). Therefore, it is important that persons in cold climates dress in layers, allowing insulation to be matched to their metabolic rate. Clothing can be added when work rates decrease and removed when work rates and metabolic heat production are increased.

TABLE 3 Effects of Work and Clothing on Sweat Loss

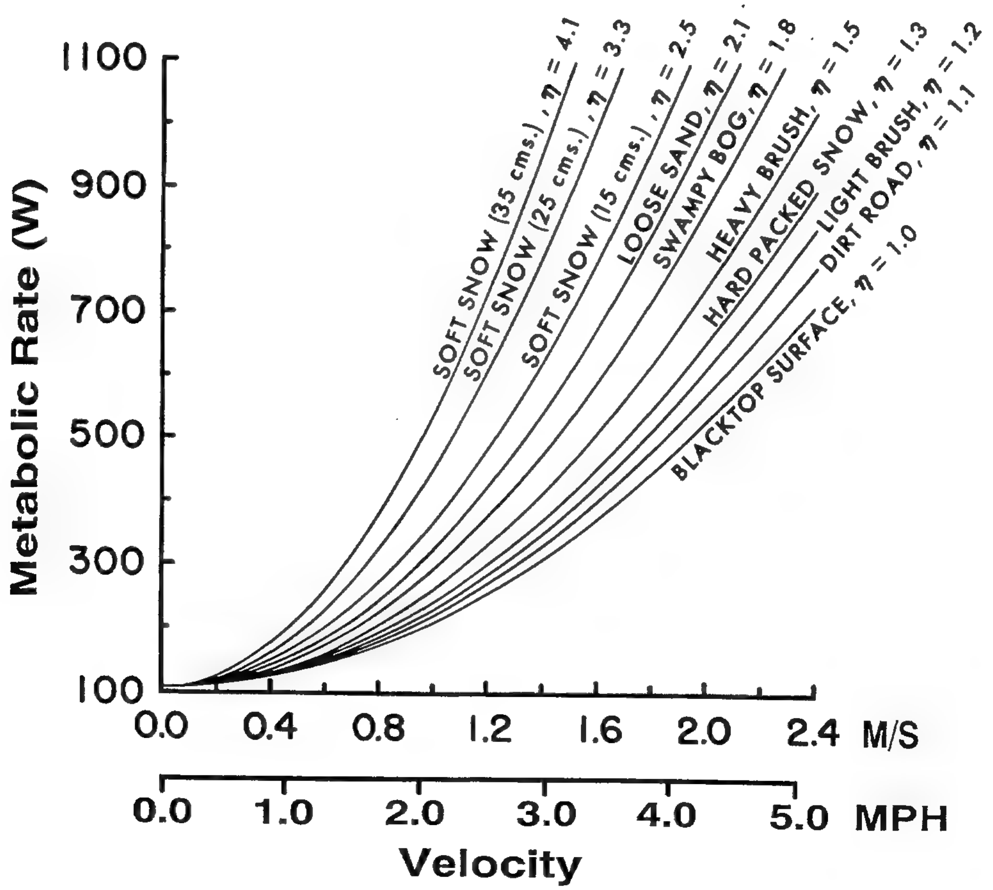
Temperature (°C)	Clo	Metabolic Rate (W)	Sweat Loss (ml/h)
0	4.0*	Rest (100)	100
-20	4.0	Rest (100)	100
0	4.0	Light-moderate (300)	1,100
-20	4.0	Light-moderate (300)	800
0	4.0	Moderate-heavy (600)	1,900
-20	4.0	Moderate-heavy (600)	1,900
0	1.9**	Moderate-heavy (600)	900
-20	1.9	Moderate-heavy (600)	400

NOTE: * = Approximate Clo for U.S. Army Extended Cold Weather Clothing System (ECWCS); ** = approximate Clo for ECWCS parka with field coat liner over Woodland Battle Dress Uniform in; W = watts.

Metabolic Cost of Movement in Cold Terrain

Figure 3 illustrates the effects of terrain associated with cold climates (e.g., snow) on the metabolic cost of movement. (Pandolf et al., 1977). Note that the metabolic cost of walking (2.5 mph) on a blacktop surface is ~ 150 watts, while movement at the same rate in deep snow increases metabolic rate by three to fourfold. The higher the metabolic rate, the greater the sweating and, hence, fluid replacement requirements. The cumbersome and hobbling effects of cold weather clothing can increase the metabolic rate during physical activity by an additional 10-20% (Amor et al., 1973; Teitlebaum and Goldman, 1972). The magnitude of this increase in metabolic rate depends on the number of clothing layers as well as the exercise or work intensity. Regardless, military operations requiring movement over snowy areas can greatly increase work rates and water losses above levels encountered during non-winter conditions.

FIGURE 3



REDUCED FLUID INTAKE IN THE COLD

Fluid Delivery

The most important factor regarding fluid intake in the cold is the logistical constraint of fluid delivery. If drinking water or other fluids cannot be provided, dehydration will undoubtedly result. While one might quickly point out that water, in the form of snow or ice, might be available, relying on such resources for drinking water is unrealistic. The resources (time and fuel) required to utilize snow and ice as a major source for drinking water during military operations are prohibitive. Therefore, drinking water must be supplied to the field at regular intervals. Orth (Orth, 1949) demonstrated this when he wrote:

"In experiments conducted last winter, it was found that at -50°F and an altitude of approximately 600 feet, using a Coleman stove it took 200 ml of fuel (gasoline) and 30-45 minutes to melt enough snow to give 600 ml of water."

He went on to conclude ....

"It was determined it would take more than six hours per day and a half a gallon of gasoline to get sufficient water for one man."

Frozen Drinking Water

Cold weather will often freeze drinking water and it can take several hours to thaw a frozen five-gallon container. Care must be given to ensure that sufficient water is protected from the cold (moved into warm vehicles or tents and canteens are worn close to the body, i.e., inside the uniform or sleeping bag).

Inadequate Drinking

An inappropriate or reduced sensation of thirst can also contribute to reduced fluid intake (Adolph et al., 1947), an observation termed "voluntary dehydration" (Greenleaf and Sargent, 1965). Voluntary dehydration occurs whenever humans

undergo severe stress (Greenleaf, 1992). This occurs not only in hot climates, but, may be more even pronounced in cold climates (Rogers et al., 1964; Wyant and Caron, 1983). Rogers and associates reported that despite marked dehydration during survival experiments in the subarctic, thirst was not displayed or commented on until individuals were brought inside and warmed. This observation raises the possibility that cold skin or reduced body core temperature might provide important input modifying thirst sensation.

In addition, persons in cold climates often voluntarily restrict fluid intake. This behavior occurs late in the day to prevent having to leave a warm tent or sleeping bag to urinate outdoors. It is from the fluid consumption at the evening meal that soldiers normally rehydrate. As a result, this behavior of underdrinking accentuates the dehydration that is carried from one day to the next.

Fluid in Cold Weather Rations

Another factor which leads to reduced fluid intake of military personnel in cold climates, is that issued cold weather rations contain little fluid. While one Ration Cold Weather (RCW) provides 4,500 kcal of nutrition, it requires 2.9 liters of fluid to rehydrate all its components. High water containing food items such as fruits and vegetables are not provided during cold operations as they would likely freeze. Importantly, if water delivery is not adequate, not only will problems of dehydration occur, but, problems of malnutrition could also develop. In addition, dehydration will act to reduce appetite, and as stated, the consumption of food stimulates drinking. As a result, dehydration and loss of appetite have a positive feedback effect to adversely influence the soldier's nutritional status.

SUMMARY

While several factors contribute to both increased fluid losses as well as reduced fluid intake, the relative contribution of each, as well as the sum of their effect on body fluid balance, is difficult to predict. This is because fluid balance in cold weather is dependent on a combination of numerous determining factors. For example, cold induced diuresis and logistical constraints in water delivery may be the

most significant factors for soldiers conducting sentry duty well forward of the main body of troops, while increased fluid losses associated with high metabolic work rates is likely to be the most significant factor for soldiers "on the move" over cold terrain.

MILITARY IMPACT/SIGNIFICANCE OF DEHYDRATION IN COLD

It is clear that military operations conducted in cold climates can have a significant effect on body fluid balance. The impact this dehydration and/or the direct effects of cold exposure can have on physical and cognitive performance, thermoregulation, and the susceptibility to cold injury are discussed below.

DEHYDRATION AND PHYSICAL AND COGNITIVE PERFORMANCE

Numerous studies report physical performance decrements during cold exposure including reductions in manual dexterity and coordination (Meese et al., 1981; Wyon, et al., 1982), muscular strength (Coppin et al., 1978; Horvath and Freedman, 1947;, Johnson and Leider, 1977) maximal power output, jumping and sprint performance (Bergh and Ekblom, 1979), submaximal and maximal exercise performance (Adolph and Molnar, 1946; Faulkner et al., 1981; Patton and Vogel, 1984), and maximal aerobic work capacity (Buskirk et al., 1958; Craig and Cummings, 1966). However, other studies report no reduction in submaximal performance (Roberts et al., 1984) or maximal aerobic power (Patton and Vogel, 1984; Rodahl et al., 1962; Saltin, 1966). Upon close examination, the apparent discrepancy between studies can be explained by a consideration of the effects of the cold environment on body core and/or muscle temperature. Maximal tension exerted during voluntary sustained contractions, as well as peak power output, are significantly reduced when muscle temperature is lowered (Clarke et al., 1958; Davies and Young, 1983). In Saltin's study (Saltin, 1966) subjects were exposed to the cold for only 30 min while in Patton's and Vogel's study (Patton and Vogel, 1984), subjects wore arctic clothing. Muscle temperatures were probably not markedly reduced, and the finding that performance was unaffected in these studies might have been expected. Therefore, both maximal and submaximal physical performance are reduced with cold exposure, only when muscle temperatures are markedly lowered.

The preceding studies did not evaluate whether dehydration further affects physical performance in the cold. Dehydration in temperate and hot climates will decrease muscular endurance and aerobic work performance (Sawka, 1992). Lynnquist et al., (Lynnquist et al., 1974) speculated that cold diuresis and resulting negative water balance are responsible for reductions in physical work capacity in the cold. However, it could be argued, their performance reductions resulted from muscle cooling. Without a control group for comparison, (i.e., cold exposed but maintained euhydrated) it is difficult to determine the direct effects of hypohydration *per se*.

Roberts et al., (Roberts et al., 1984) examined the effects of dehydration on physical performance in the cold. In this study, hydration status was controlled. In one group of subjects, euhydration was maintained, while in a second group, subjects were dehydrated (by fluid restriction and exercise) 3.5% of body weight. Subjects performed two endurance exercise tests (30 min of cycle egometry at approximately 75% of maximal oxygen consumption). One endurance test was performed in a temperate environment (65-70°F) and one during cold air (32°F) exposure. There was no significant effect of cold or hypohydration on submaximal exercise performance. However, it could be argued that the exercise duration and/or intensity might have been too short or too low to accentuate differences among trials.

While many studies report that cold exposure reduces cognitive performance, only one study actually that examined the effects of dehydration on cognitive performance in the cold. Banderet et al., (Banderet et al., 1986) studied two groups of 18 subjects; for one group euhydration was maintained while the second group was dehydrated (prior fluid restriction and exercise) by 2.5% body weight. Hypohydration negatively influenced cognitive performance as assessed by measures of coding, number comparison, computer interaction, pattern comparison, and grammatical reasoning.

Since there are limited data on dehydration and performance in the cold, and since a soldier in the cold need not be a "cold soldier", we might estimate the effects of dehydration on performance in the cold by examining numerous well-controlled studies of dehydration in temperate or hot environments. Sawka and Pandolf (Sawka and Pandolf 1990) reviewed studies examining effects of dehydration on physical

performance. From their summary tables, it appears that dehydration representing as little as 3% loss of body weight, can result in significant reductions in muscular strength, muscular endurance, and anaerobic work capacity; although in several other studies, no significant changes in the above parameters were reported. Likewise, dehydration seems to cause significant reductions in maximal aerobic power and maximal work capacity with decrements beginning with as little as a 2% body weight loss. It is also apparent that the magnitude of performance decrement is directly related to the level of dehydration and is accentuated by heat stress (Sawka, 1992). Clearly, further study is needed to determine the direct effects of dehydration on physical and cognitive performance during cold exposure.

DEHYDRATION AND THERMOREGULATION

Dehydration has negative effects on thermoregulation during heat stress. A fluid loss representing as little as 1% body weight can alter exercise thermoregulation (Greenleaf and Harrison, 1986) and dehydrated persons are more susceptible to heat exhaustion (Sawka, 1992). Furthermore, Adolf and associates (Adolf et al., 1947) indicated that body fluid losses can become life threatening as they exceed 10% of body weight.

There are a variety of mechanisms responsible for the effects of dehydration on thermoregulation. Sawka (Sawka, 1992) demonstrated that when individuals are hypohydrated, the onset of sweating was delayed i.e., body core temperature needed to rise significantly more to initiate sweating when hypohydrated compared to euhydrated. For any given core temperature, sweating rate was significantly less when hypohydrated compared to when euhydrated (Sawka, 1992). With reduced rates of sweating during hypohydration, less evaporative heat loss occurs. This will result in additional heat storage and potentially a greater rise in body core temperature. The greater rise in body core temperature has important implications for physical performance and for thermal injury/illness as well.

The overall effect of dehydration on thermoregulation is dependent on a combination of factors that determine whether an overall gain or loss in body heat storage will occur. For example, in moderately cold climates when individuals are

wearing heavy clothing and are performing heavy work or exercise, it is conceivable that dehydration will exacerbate the core temperature rise and increase heat strain. On the other hand, in severe cold, or when work rates are low and body heat losses exceed heat production, dehydration probably has little effect on core temperature elevation, but might accentuate peripheral cooling (see below). In addition, dehydration appears to affect a person's perception of effort. Montain and Coyle (Montain and Coyle, 1992) demonstrated significantly higher ratings of perceived exertion during exercise when little or no water was ingested compared to trials in which large or moderate amounts of fluid were ingested.

DEHYDRATION AND COLD INJURY SUSCEPTIBILITY

It is often suggested that dehydration increases a person's susceptibility to peripheral cold injuries (Gamble, 1994), and numerous case reports indicate that patients suffering from peripheral cold injury are often dehydrated. However, the direct evidence demonstrating that dehydration itself significantly increases the risk for peripheral cold injury is limited.

Roberts and Berberich (Roberts and Berberich, 1988) conducted a study which assessed dehydration effects on peripheral and central body cooling during cold exposure. Two groups of subjects, one maintained euhydration and the other dehydrated by 4.6% of body weight (exercise and fluid restriction), were exposed to cold air on four separate occasions (i.e., two days prior to dehydration and two days after being dehydrated). Subjects wore standard military cold weather clothing and after 15 min their gloves and glove liners were removed. While core temperature responses were similar, dehydration resulted in a greater vasoconstriction to the hand as evidenced by greater finger cooling. These data indicate that dehydration might blunt cold induced vasodilation and increase the susceptibility to peripheral cold injury. However, considerable variability in the peripheral cooling responses existed, and the groups appeared dissimilar even before being dehydrated.

Another study on the effects of dehydration on thermoregulation during cold exposure was conducted by Roberts and colleagues (Roberts et al., 1984). They

report that during 90 min exposure to 0°C air, greater hand cooling occurred in persons dehydrated by 3.5% of body weight. While the above data are suggestive that dehydration might increase one's susceptibility to peripheral cold injury, additional work is clearly merited.

SUMMARY CONTENTS

In summarizing the potential effects of dehydration on soldier's health and performance in cold environments, we again quote Orth (Orth 1949):

"The lack of sufficient fluids in the diet to maintain a positive water balance causes at first a change in disposition, sullenness, loss of appetite, chronic thirst, discipline begins to suffer... and finally failing physical efficiency. The final step is dehydration exhaustion, this can take place in 3-4 hours in the desert, but it also can take place in as little as two days in the Arctic where solid water abounds."

COUNTERMEASURES TO DEHYDRATION

The best way to prevent dehydration is to ensure adequate fluids are ingested. However, due to various factors that cause dehydration in cold environments, this is not an easily solved problem. Recent efforts have been made to investigate potential countermeasures to prevent or blunt cold-induced dehydration and hence the related decrements to performance and health. Glycerol, a nontoxic, naturally occurring metabolic by-product and food additive, has been shown to improve fluid retention over standard electrolyte beverages or water alone. We recently demonstrated in a temperate environment that drinking approximately 1.75 liters of water in attempt to achieve hyperhydration, only 33% of the fluid was retained following 3 hr (the rest was eliminated by the kidney), whereas if the same volume of water had approximately 70 grams of glycerol added nearly a doubling in fluid retention occurred, i.e., 59% (Freund et al., 1993). These experiments were duplicated during cold air exposure. Again greater fluid retention was found following the ingestion of glycerol and water

versus water (Freund et al., 1994). In addition to improving fluid retention and adding calories to water, glycerol also reduces the freezing point (e.g. a 30% glycerol solution reduces the freezing point 9°C below water). Hence, adding glycerol might also be effective in reducing problems associated with drinking water freezing.

From the above experiments, we demonstrated that differences in fluid retention with glycerol were the result of a blunted increase in urine flow. Importantly, the differences in urine flow were entirely accounted for by differences in free water and not osmotic clearance (Freund et al., 1993, Freund et al., 1994). Although further study is required, these studies provide evidence that differences in antidiuretic hormone response may be the mechanism responsible for improved fluid retention with glycerol.

Future countermeasures for dehydration in the cold could include pharmacological interventions such as the administration of antidiuretic hormone analogs or perhaps even combined treatments e.g., glycerol and antidiuretic hormone. It is only through innovative experimentation that the health and performance of soldiers deployed to harsh environments can be optimized.

CONCLUSIONS

In cold climates body fluid losses can be similar to those in hot environments and can result from sweating and increased respiratory water losses as well as cold induced diuresis.

Fluid intake in cold environments can be reduced as a result of logistical constraints in fluid delivery, problems with water freezing, reduced thirst sensation, and voluntary fluid restriction.

Dehydration negatively influences physical and cognitive performance as well as thermoregulation and possible susceptibility to peripheral cold injury.

Ingestion of glycerol in drinking water might be an effective countermeasure to reduce or delay cold-induced dehydration and the associated decrements to performance during cold weather operations.

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